Hardware Prototyping of RIS-Aided Wireless Communication

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***Abstract*—Here we are proposing an efficient algorithm to calculate Optimum phase shift vector($\overline{\Psi}_{opt}$) for training the reflected beam form the Reflective Intelligent Surface(RIS) to a given azimuth and elevation angle (θ_r, ϕ_r). Here we assume (a) Line of Sight(LoS) wireless channel between the Access Point(AP) and RIS (b) No direct path exists between AP and UE.**

***Index Terms*—Reflective Intelligent surface**

I. RIS-Aided Beamforming Method

THE RIS will scatter or reflect the incident wave in a way determined by its configuration. The RIS can aid the communication system by optimizing its reflection coefficients to maximize the received signal power. This effectively means that the RIS elements should make their individually reflected signals reach the receiver in phase (up to the granularity set by the hardware). Since we assume an LoS channel from the RIS to the receiver, the optimization will essentially result in a reflected beam in the angular direction leading to the receiver.

II. Mathematical Model

As shown in Fig. 2, the RIS has N_H columns and N_V rows of sub-atoms(reflectors). Distance between any two adjacent reflectors in a row or in a column is designed to be $\frac{\lambda}{2}$, where λ is the wavelength of incident/reflected ray.

We assume that the positions of RIS and AP are fixed. The only variable is the direction of reflected beam from RIS towards UE in terms of (θ_r, ϕ_r), where (θ_r, ϕ_r) are the reflected azimuth and elevation angles respectively. The problem being studied here is - for a given (θ_i, ϕ_i), how we can calculate the $\overline{\Psi}_{opt}$ so that the reflected beam from RIS is trained towards the desired direction (θ_r, ϕ_r) .

We use far-field approximation for making the mathematical analysis simpler, and the minimum distance between the AP to RIS, and RIS to UE is expected to be $\frac{\lambda}{2} \cdot \max(N_V, N_H)$ [1]

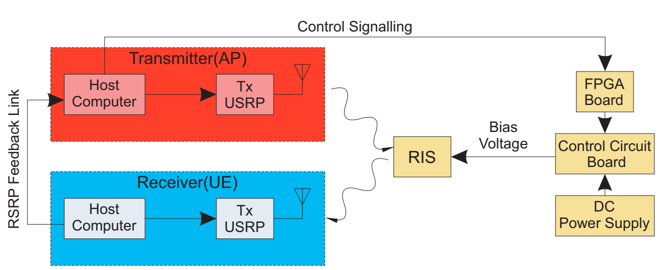

Fig. 1: System diagram for the RIS-aided communication system.

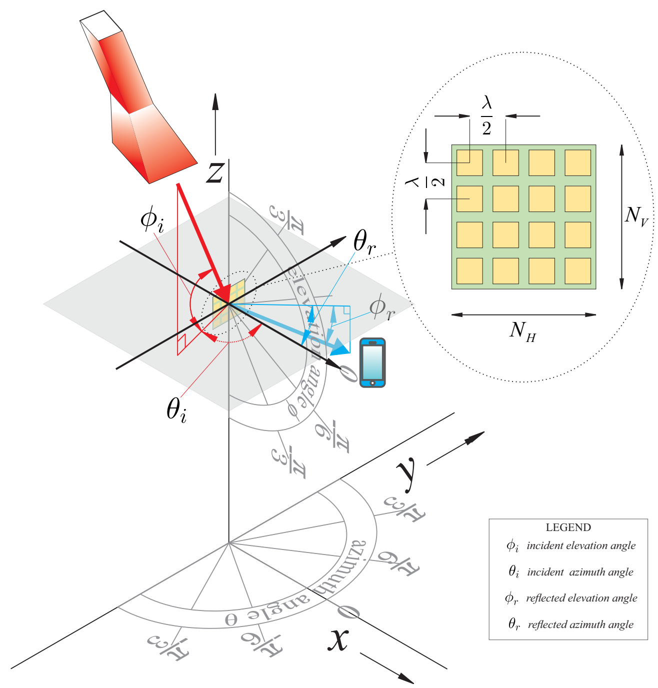

Fig. 2: The coordinate system describing the RIS with N_H columns and N_V rows. The incident ray and incident angles are indicated by red colour and reflected ray and reflected angles are indicated by cyan color.

A. Definition of azimuth and elevation angle (θ, ϕ)

Azimuth angle θ is defined as angle from positive x-axis towards positive y-axis. Elevation angle ϕ is defined as angle from positive x-axis towards positive z-axis. By default, all angle measurements are taken with RIS as origin.

B. Regarding the phase steering resolution of RIS

For a practical RIS, there will be a finite resolution for the phase shifts its reflectors can introduce. For example, if the RIS has 1-bit resolution, it can either introduce a phase-shift(ψ) of 0 or a phase-shift of π ($\psi \in \{0, \pi\}$). For an RIS of 2-bit resolution, $\psi \in \{-\frac{3\pi}{4}, -\frac{\pi}{4}, +\frac{\pi}{4}, +\frac{3\pi}{4}\}$.

C. LoS Channel Modelling

Here we assume that the distance between two sub-atoms in a row(d_x) and column (d_y) is $d_x = d_y = \frac{\lambda}{2}$, where λ is the wavelength. The array response vector $\mathbf{a}(\theta, \phi)$ is given by [2, 3]:

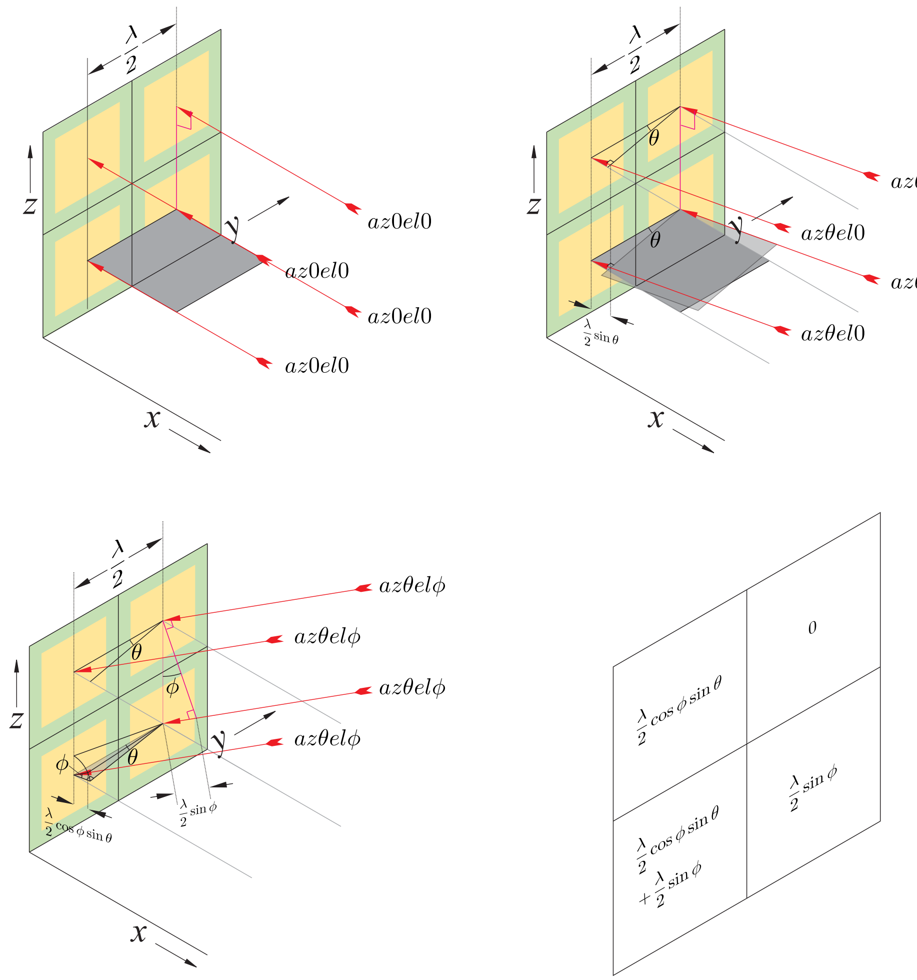

Fig. 3: Pictorial illustration of how LoS channels are calculated. Here we have taken a simple example of $[2 \times 2]$ RIS. The bottom-right figure shows the relative path difference, taking the ray incident at top right reflector as reference. This result can be easily scaled up to $[N_V \times N_H]$ RIS. To get the phase difference, substitute $\lambda = 2\pi$

$$\mathbf{a}(\theta,\phi) = \mathbf{a}_{az}(\theta,\phi) \otimes \mathbf{a}_{el}(\phi) \tag{1}$$

where $\otimes$ denotes the Kronecker product. $\mathbf{a}_{az}$ and $\mathbf{a}_{el}$ represent the array response vectors of a uniform linear array along the y-axis(azimuth) and the z-axis(elevation) respectively.

$$\mathbf{a}_{az}(\theta,\phi) = \left[1, e^{\frac{-j2\pi}{\lambda} d_y \ \cos\phi \sin\theta}, \cdots, e^{\frac{-j2\pi}{\lambda} d_y \ (N_V-1) \ \cos\phi \sin\theta}\right]^{\mathrm{T}}, \tag{2}$$

$$\mathbf{a}_{el}(\phi) = \left[1, e^{\frac{-j2\pi}{\lambda} d_z \cdot \sin\phi}, \cdots, e^{\frac{-j2\pi}{\lambda} d_z \cdot (N_H-1) \ \sin\phi}\right]^{\mathrm{T}}. \tag{3}$$

In our design, $d_y = d_z = \frac{\lambda}{2}$. From this result as well as from Fig. 4, it can be observed that a Line of Sight(LoS) Channel can be modelled as follows -

$$h = e^{-j\pi \cdot n \cdot sin\theta \cdot cos\phi} \cdot e^{-i\pi \cdot m \cdot sin\phi} \cdot e^{i\varphi} \tag{4}$$

where,

- θ is the azimuth angle
- ϕ is the elevation angle
- m is the index of RIS sub-atom row wise ($m \in \{0, 1 \cdots N_H - 1\}$)
- n is the index of RIS sub-atom column wise ($n \in \{0, 1 \cdots N_V - 1\}$)
- φ is the initial phase, or phase of the wave incident at the element $m = 0, n = 0$

Here we are not taking free space path loss into consideration. Hence, the magnitude(envelope) of the fading coefficient has been normalised to unity.

Thus, channel between AP and RIS will be

$$h_1 = e^{-j\pi \cdot n \cdot sin\theta_i \cdot cos\phi_i} \cdot e^{-j\pi \cdot m \cdot sin\phi_i} \cdot e^{j\varphi} \tag{5}$$

and channel between RIS and UE will be

$$h_2 = e^{-j\pi \cdot n \cdot sin\theta_r \cdot cos\phi_r} \cdot e^{-j\pi \cdot m \cdot sin\phi_r} \cdot e^{j\varphi} \tag{6}$$

III. Optimum phase shift(Ψ_{opt})calculation

From Fig. 4(d), we can notice that for a given set of incident and reflected angles - (θ_i, ϕ_i) and (θ_r, ϕ_r), in order to get the

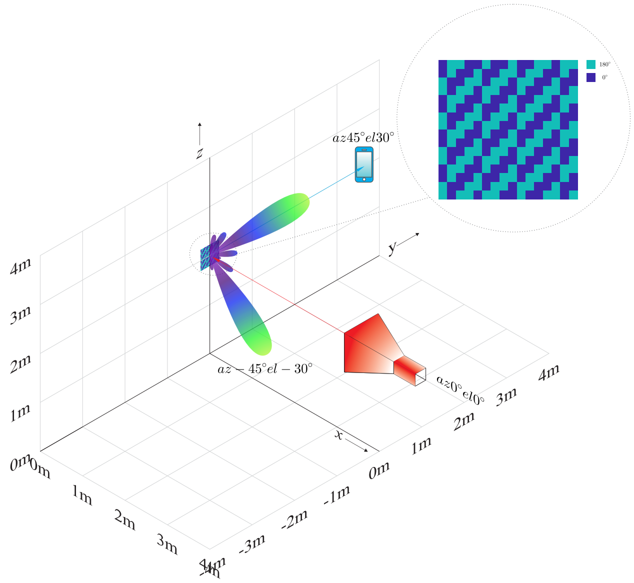

Fig. a

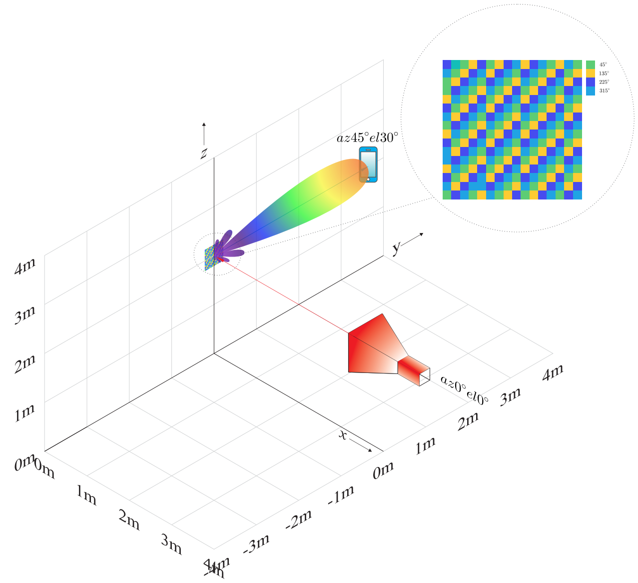

Fig. b

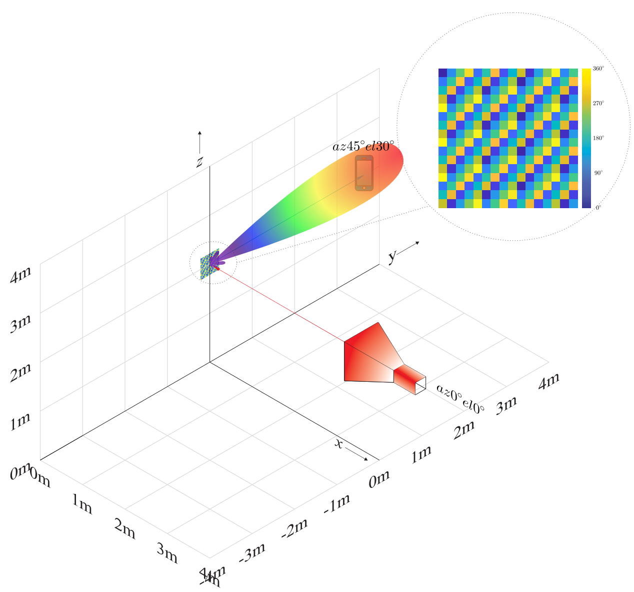

Fig. c

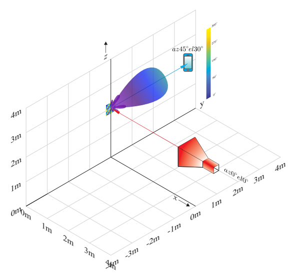

Fig. d(i)

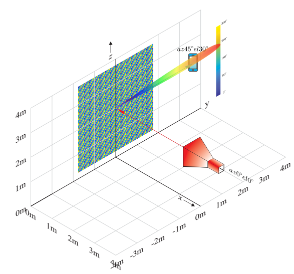

Fig. d(ii)

Fig. d

Fig. 4: (a) Example of a beamforming that happens at $\theta_r = 45°, \phi_r = 30°$, where AP is located at $\theta_r = 0°, \phi_r = 0°$. RIS angle-resolution = $1 - bit$. $N_V = 16, N_H = 16$. Note the spurious lobes beside the main lobe, caused due to finite angle-resolution.(b) RIS angle-resolution = 2-bit. Note the spurious lobes got reduced when we increased the RIS angle-resolution. (c) RIS angle-resolution = ∞-bit. Here spurious lobes are further minimised.(d) Fig. d(i) has $[8 \times 8]$ RIS, Fig. d(ii) has $[64 \times 64]$ RIS. If we increase the number of sub-atoms, the beam width will get narrowed down.

desired beamforming, we should introduce a phase shift of $\overline{\Psi}_{opt}$, where

$$\overline{\Psi}_{opt} = \begin{bmatrix} \psi_{0,N_V-1} & \psi_{1,N_V-1} & \cdots & \psi_{N_H-1,N_V-1} \\ \cdots & \cdots & \cdots & \cdots \\ \psi_{01} & \psi_{11} & \cdots & \psi_{N_H-1,1} \\ \psi_{00} & \psi_{10} & \psi_{20} & \psi_{N_H-1,0} \end{bmatrix}_{N_V \times N_H} \tag{7}$$

$$\begin{aligned} \psi_{mn} =& m\pi(\cos\phi_i \sin\theta_i + \cos\phi_r \sin\theta_r) \\ &+ n\pi(\sin\phi_i + \sin\phi_r) \\ =& m\pi c_{azim} + n\pi c_{elev} \end{aligned} \tag{8}$$

where,

$$\begin{aligned} c_{azim} &= \sin\theta_r \cos\phi_r + \sin\theta_i \cos\phi_i, \\ c_{elev} &= \sin\phi_r + \sin\phi_i \end{aligned} \tag{9}$$

ψ_{mn} is the optimum phase shift to be given to the sub-atom located in m^{th} column and n^{th} row in the RIS, $m \in \{0, 1, ..N_H - 1\}$, $n \in \{0, 1, ..N_V - 1\}$

If we write Equation 8 in matrix form, it will be

$$\boxed{\Psi_{opt} = \Lambda_{azim} \cdot c_{azim} + \Lambda_{elev} \cdot c_{elev}} \tag{10}$$

$$\Lambda_{azim} = \begin{bmatrix} 0 & \pi & 2\pi & \cdots & (N_H-1)\pi \\ 0 & \pi & 2\pi & \cdots & (N_H-1)\pi \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \pi & 2\pi & \cdots & (N_H-1)\pi \end{bmatrix}_{N_V \times N_H} \tag{11}$$

$$\Lambda_{elev} = \begin{bmatrix} 0 & 0 & \cdots & 0 \\ \pi & \pi & \cdots & \pi \\ 2\pi & 2\pi & \cdots & 2\pi \\ \vdots & \vdots & \vdots & \vdots \\ (N_V-1)\pi & (N_V-1)\pi & \cdots & (N_V-1)\pi \end{bmatrix}_{N_V \times N_H} \tag{12}$$

IV. Proposed User Equipment(UE) Search Algorithm

Since we know the Ψ_{opt} matrix, to search for the location of UE, all we need to do is plug in all possible values of (θ_r, ϕ_r) in the formula to calculate Ψ_{opt},and check the received signal power at UE. The (θ_r, ϕ_r) pair that gives the maximum received signal strength at UE, will be the direction towards UE.

When we practically implement this algorithm, we have to set a certain granularity to run this search algorithm. For instance, if we set the granularity as $\Delta_{azim}, \Delta_{elev}$ we divide the range of θ (viz. $[-\frac{\pi}{2}, \frac{\pi}{2}]$) into Δ_{elev} equal parts, and the range of ϕ (viz. $[-\frac{\pi}{2}, \frac{\pi}{2}]$) into Δ_{azim} equal parts. Thus, a total of $\Delta_{azim} \times \Delta_{elev}$ calculations of received power at UE ought to be done.

The higher the value of granularity, better will be the UE tracking accuracy, but higher will be the latency. Complexity of Algorithm 1 depends on the search granularity $\Delta_{azim}, \Delta_{elev}$. The reason why search granularity has to be directly proportional to number of reflectors is that, as the no: of reflectors increases, the beam gets more and more narrower/ pencil shaped (Fig. 4d) When we performed the experiment practically, a minimum of $\Delta_{azim} = N_H$ and $\Delta_{elev} = N_V$ was required to avoid any false positives for the UE search algorithm. Here Δ_{azim} is the search granularity along azimuth plane and Δ_{elev} is the search granularity along elevation plane. Thus, the minimum number of feedback iterations required is $N_H \cdot N_V$.

Notations: h_1 is the channel from AP to RIS, and is an $[L \times 1]$ complex vector, where $L = N_H N_V$ is the total number of reflectors in the RIS. h_2 is the channel from RIS to UE, and is an $[L \times 1]$ complex vector. Ψ is an $N_V \times N_H$ real matrix. **vec()** is a column-wise vectorization operation on a matrix, $e^{[]}$ is a element-wise exponential operation, $\odot$ is element-wise multiplication operation.

Algorithm 1 UE Search Algorithm

Input: The feedback of RX signal power $rssi$.
Output: $(\hat{\theta}_{UE}, \hat{\phi}_{UE}) = \underset{\theta,\phi}{\operatorname{argmax}}\, rssi(\theta, \phi)$: The (θ, ϕ) pair which fetches the highest $rssi$.
Initialize:

$$\theta_{sweep} \leftarrow -\frac{\pi}{2} + \frac{\pi}{\Delta_{azim}} \times \{0, 1, ...N-1\} + \frac{\pi}{2\Delta_{azim}}$$

$$\phi_{sweep} \leftarrow -\frac{\pi}{2} + \frac{\pi}{\Delta_{elev}} \times \{0, 1, ...N-1\} + \frac{\pi}{2\Delta_{elev}}$$

for each $\theta \in \theta_{sweep}$ **do**
  for each $\phi \in \phi_{sweep}$ **do**

$$c_{azim} \leftarrow \sin\theta_r \cos\phi_r + \sin\theta_i \cos\phi_i$$
$$c_{elev} \leftarrow \sin\phi_r + \sin\phi_i$$
$$\Psi \leftarrow \Lambda_{azim} \cdot c_{azim} + \Lambda_{elev} \cdot c_{elev}$$
$$rssi \leftarrow \left| \sum_L \left(h_1 \odot e^{[i \cdot \mathbf{vec}(\Psi)]} \odot h_2 \right) \right|^2$$

  end for
end for

$$(\hat{\theta}_{UE}, \hat{\phi}_{UE}) \leftarrow \underset{\theta,\phi}{\operatorname{argmax}}\, rssi(\theta, \phi)$$

return $(\hat{\theta}_{UE}, \hat{\phi}_{UE})$

References

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